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PASADENA, CALIFORNIA

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A STUDY OF PRESSURE DROP
IN
HELICAL COILS

Thesis by

Lieutenant Commander OLIVER S. DUKE, U.S. Navy

Library
U. S. Naval Postgraduate School
Annapolis, Md.

In partial fulfillment of the requirements for
the degree of
Aeronautical Engineer

California Institute of Technology
Pasadena, California
September, 1948

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The author is further indebted to Lieutenant Commander [illegible]. H. McEllicott, U. S. Navy. The laboratory work and the tables and curves contained herein resulted from a joint effort of Lt. Cmdr. McEllicott and the author.

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ABSTRACT

This study was made to investigate the increase in pressure drop through a helix over that through a straight pipe and to study the variables involved. The pressure drops in ten helices and seven straight pipes were observed over a range of Reynolds Numbers.

The results indicate that the increase in pressure drop due to the helical shape is a function of tube diameter, helix diameter, relative roughness, and possibly Reynolds Number. There is some indication that relative roughness may be the most important of these variables. However, the data obtained are insufficient to justify the formulation of an empirical equation for the curvature correction.

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INTRODUCTION

The literature reveals little on the subject of pressure drop in helical coils. Mr. B. T. Morris of the Aerojet Engineering Corporation and Dr. H. S. Seifert of the Jet Propulsion Laboratory, California Institute of Technology, have each used a straight pipe correction factor to estimate the pressure drop of cooling coils for small rocket motors. This study is an incomplete effort to formulate such a correction factor.

The procedure attempted was to compare the pressure drop through several helical coils with the pressure drop through equivalent straight tubes of equal relative roughness. However, the roughness of the test specimens could not be controlled and equivalent relative roughness of the straight and helical specimens was not achieved. Consequently, the comparison was made between the observed friction factors of the helices and straight pipe friction factors predicted from the curves of Reference 1. No attempt was made to correlate the results with a theoretical study of flow phenomena.

The scope of the work is limited in several other respects. All conduit samples studied were of small circular cross-section and the upper mean velocity of flow was arbitrarily limited to fifty feet per second. Consequently, the results are confined to a small range of Reynolds Numbers in the turbulent flow regime.

The work was done during April through August, 1948, at the Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California.

EXPLANATION OF SYMBOLS

f	Friction factor, dimensionless. Defined by the Darcy equation for pressure drop in a straight circular conduit: $\Delta P = f(L/D)d(v^2/2g)$
f'	Predicted friction factor for straight conduit from known relative roughness ratio and Reynolds Number (Cf. Ref. 1)
f_o	Observed friction factor $= \dfrac{\Delta P_{(coil)}\ 2Dg}{L d v^2}$
ΔP	Pressure drop, lb/ft^2
v	Mean flow velocity, ft/sec.
W	Flow rate, lb/sec.
g	Acceleration due to gravity, 32.2 ft/sec.
d	Specific weight of fluid, lb/ft^3
D	Diameter of conduit, inches
L	Length of conduit, inches
D_h	Mean diameter of helix, inches
ν	Kinematic viscosity, ft^2/sec.
Re	Reynolds Number, $(v/\nu)(D/12)$, dimensionless
r	Roughness as measured by profilometer, micro-inches
r/D	Relative roughness ratio from profilometer value
ε/D	Relative roughness ratio from absolute roughness (Cf. Ref. 1)
Ac	Conventional correction factor for helical pressure drop as used by Morris and Seifert: $A_c = 1 + 3.5(D/D_h)$

Hc' Correction factor for increase of pressure drop of helical coil over that of equivalent straight pipe as determined experimentally in this study:

$$Hc' = \frac{\Delta P \text{ (coil) } D \ 2g}{f' \ L \ d \ v^2} = \frac{f_c}{f'}$$

EQUIPMENT AND PROCEDURE

EQUIPMENT. The equipment used consisted essentially of:

(a) a pump to supply a variable flow of water, the working fluid,

(b) two piezometer ring pressure pick ups,

(c) a water manometer, a mercury manometer, and pressure gauges for measuring pressure drop,

(d) a weighing tank, scale, and stop watch for determining flow rates, and

(e) the test sections of straight tubing and helical coils.

A schematic sketch of the equipment is shown in Fig. 1.

Helical Test Sections. The helical test sections were formed from seamless drawn stainless steel tubing of 0.375 inches outside diameter and 0.035 inches wall thickness. The roughness of the interior surface of this tubing varied from piece to piece which made necessary the study of several straight sections having different values of interior roughness.

The helices are described in detail in Table I, and the manufacturing technique is set forth in Appendix B.

Straight Test Sections. The straight test sections were of standard commercial seamless drawn stainless steel tubing of 0.50 inches outside diameter and 0.035 inches wall thickness. They were four feet in length and of various values of roughness. In order to vary the roughness, the interior surface of these sections was treated by two different processess: sand blasting and electrolytic polishing. It was because these two processes could not be applied to the 0.375 inch tubing that the 0.50 inch tubing was chosen for the straight test sections. The 0.375 inch tubing had previously been chosen for the helices due to its ease of fabrication. The details of the straight test sections are listed in Table II.

Piezometer Ring Pressure Pick Ups. The piezometer ring pressure pick ups were short machined stainless steel sections installed on the straight leads at the entrance and exit of each helix. They consisted of a polished conduit equal in diameter to the tubing and drilled with three small radial holes equally spaced on the circumference. The holes were manifolded by a hollow welded collar which was fitted with a tubing connection to which the manometers and gauges were connected.

PROCEDURE. The following is a step-by-step description of the procedure employed:

(1) Install test section in apparatus and wash out for fifteen minutes at a flow rate well above the maximum test value.

(2) Reduce flow rate to produce about four inches

of water pressure drop, allow flow to stabilize, and read pressure drop.

(3) Simultaneously with (2) collect the full flow of water in the weighing tank for a timed period. Record the weight of water and time of flow.

(4) Increase flow rate to reach maximum in 20 to 30 steps; record readings at each step.

(5) Correct observed pressure drops for drop due to pressure pick-ups, joints, straight leads, and gauge calibration (if necessary).

(6) Measure water temperature and record density and viscosity (Cf. Ref. 2 and 3). (No change in water temperature occurred during the test of any one section in this study due to the large size of the sump used.)

(7) Compute Reynolds Number for each step.

(8) Compute friction factor, f_o, for each step.

(9) Plot f_o against Re for the section.

(10) Cut up test section and measure roughness.

In order to eliminate the pressure drop due to the pressure pick-ups (step 5 above), the following procedure was used. The two pick-ups employed in the test were connected to each end of a one-foot straight length of the test section tubing. A complete test of this short section was made and a curve of pressure drop versus flow rate was constructed. This curve was used to determine the deduction to be applied to the observed pressure drop of the straight test section at each flow rate. In calculating f_o, the effective length of the test section was consequently reduced one foot from the measured value.

The helical test sections, because the straight leads varied in length from coil to coil, required a small additional correction. The effect of the pressure pick-ups plus six inches of straight lead was corrected for in the same manner as that described above for the pick-ups plus one foot on the straight sections. The pressure drop through the length of straight leads in excess of six inches was corrected for by a curve of pressure drop per unit length versus flow rate. The data for this curve were obtained as follows:

(a) three representative 0.375 inch straight tubing samples, eight feet in length, were tested over the range of flow rates of the parent tests,

(b) the tests of these three samples were corrected for the effects of the pressure pick-ups plus one foot of length as outlined above,

(c) for each flow rate the average pressure drop of the three tubes was divided by the length less one foot (seven feet),

(d) this value of pressure drop per unit length was plotted against flow rate to yield the desired curve.

These two corrections to the observed pressure drop of the helices can be summarized as follows: a deduction, taken from the first curve, for the drop due to the pressure pick-ups plus six inches of straight lead, and a deduction for the remaining straight leads obtained by multiplying the total length of leads less six inches by the figure obtained from the second curve.

Calculations. Steps 7 and 8 under procedure entail the following calculations:

(a) Conversion of flow rate to mean flow velocity:

$v = W/dA$ where

v = velocity in feet per second

W = flow rate in pounds per second

d = specific weight of water at working temperature in pounds per cubic foot (Cf. Ref. 3)

A = cross sectional area of conduit in square feet

(b) Calculation of Reynolds Number:

$Re = (v/\nu)(D/12)$ where

v = velocity, ft/sec.

ν = kinematic viscosity, ft^2/sec.

D = inside diameter of conduit, inches.

(c) Calculation of friction factor:

$f_o = (\Delta P/d)(D/L)(2g/v^2)$ where

ΔP = observed pressure drop, lb/ft^2

d = specific weight, lb/ft^3

D = inside diameter of conduit, inches

L = length of conduit, inches

g = acceleration due to gravity, 32.2 ft/sec^2

v = velocity, ft/sec.

ASSUMPTIONS AND LIMITATIONS

ASSUMPTIONS. Assumptions Concerning Roughness.

Several assumptions were made in order to attack the problem with any reasonable expectation of success. It was necessary to consider carefully the matter of roughness in the tubes. Roughness can be characterized by the degree of roughness, or actual size of surface irregularities, and by the nature of the roughness, or shape and spacing of the surface irregularities. It is known that a variation in a conduit of either the degree or nature of the roughness will vary the frictional pressure drop of the conduit. The degree of the roughness was subject to measurement by profilometer but the nature of the roughness could be judged only by visual inspection. Consequently, it was necessary to assume that a noticeable slight change in the nature of the roughness of a tube after it had been formed into a helix had a negligible effect on the pressure drop. It also was assumed that the treatment of the inside surface of the tubes by sand blasting and electrolytic polishing did not change appreciably the nature of the roughness.

Other Assumptions. The accuracy of the experimental data is dependent upon the validity of certain other assumptions. The roughness value used for a test section was arrived at by averaging profilometer readings of samples taken from each one foot length of the test section. The previously described procedure for eliminating the effects of the pressure taps and straight leads of the helices includes the assumption that these effects when measured with a short tubing section are the same as exist under actual test conditions.

Upon completion of the experimental program, when the test sections were cut up to measure their surface roughness, two conditions which seriously hampered the analysis of results were brought to light. Helices 1 and 2 were found to be locally fouled with small particles of "Cerrasafe". This radical change in roughness and cross-sectional area which was not shown by the profilometer measurements was assumed to be the cause of the very high friction factors of these two sections. Consequently, the data from these two helices, while included in the report, were not considered in the analysis.

The second condition discovered upon cutting the test sections was that the relative roughness, r/D, of the one-half inch straight tubes was lower than that of the three-eighths inch tubing of the helices. The initial estimate of the maximum roughness obtainable by the sand blasting process was 100 micro-inches while the actual maximum obtained was 45 micro-inches. This yielded much lower relative roughness values than expected. Consequently, it was impossible to make a direct comparison between straight and helical tubes of identical relative roughness as was originally intended. Time prevented the preparation and test of any additional roughened sections. Consequently, an attempt was made to predict from Reference 1 the friction factors of straight tubes with which to compare the observed friction factors of the helical coils.

Use of r/D for ϵ/D. It was found that the test sections were so nearly smooth that f could be accurately predicted from the curve of Reference 1 using the value of r/D as equivalent to ϵ/D. It should be emphasized that this establishes no equivalence between r/D and ϵ/D since f is highly insensitive to variations in ϵ/D in the regime under consideration. However, the observed friction factors, f_o, of all the straight sections tested were compared with the friction factors predicted as above and were found to agree within four per cent.

With this confirmation, straight tube friction factors were predicted from the values of r/D of all the helical test sections. The analysis was then based upon the comparison of f' and f_o for each helix just as if f' were obtained from a straight test section as was originally planned.

Summary of Assumptions. The assumptions are summarized below:

(a) The nature of the roughness of a straight tube does not change when the tube is formed into a helix.

(b) The nature of the roughness of a straight tube does not change when the surface is electropolished or sand blasted.

(c) The effective roughness of a piece of drawn stainless steel tubing can be obtained by averaging the values of samples from each one foot length of the piece.

(d) The pressure drop through the pressure pick-ups and the straight leads of a helix can be estimated by testing the pick-ups with a straight section of tubing identical with that of the helix.

LIMITATIONS. The limitations on this study are listed below:

(a) The upper limit of mean water velocity studied is 50 feet per second.

(b) The range of Reynolds Numbers is 10,000 to 100,000.

(c) Test sections include only three-eighths and one-half inch tubing of circular cross section.

(d) The only fluid studied is water.

(e) No attempt is made to correlate the results with theory.

Recommendations for further investigation of the subject are contained in the final section of this report.

RESULTS AND DISCUSSION

The Nature of the Curvature Correction. Two points of view are available in considering the nature of the curvature correction. The increase of pressure drop of the helices over that of the equivalent straight tubes can be computed either as:

(a) an increase in the straight tube friction factor, or

(b) a correction factor, Hc', to be used with the straight tube friction factor in the Darcy equation.

In the first case the observed friction factor, fo, is computed from the observed pressure drop by the Darcy equation, $fo = \Delta P(D/Ld)(2g/v^2)$, and the increase expressed as a percentage, thus: $\frac{fo-f'}{f'}$. In the second case the correction factor is computed from the same equation using the straight tube friction factor thus: $Hc' = (\Delta P/f')(D/Ld)(2g/v^2)$. It is apparent that $Hc' = fo/f'$ and that $\frac{fo-f'}{f'} = Hc'-1$. Consequently, the per cent increase in friction factor due to curvature will be referred to hereinafter as simply Hc'-1.

The Variables Involved. This curvature effect might be attributed to any or all of the following variables:

(a) N, the number of turns of the helix

(b) Re, the Reynolds Number

(c) D, the tube diameter

(d) Dh, the helix diameter, and

(e) r, the roughness of the tube.

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Consequently, Hc' may be tentatively considered to be of the form, 1 + φ(N, Re, D, Dh, r). However, previous experience indicates that the ratios r/D and D/Dh are significant parameters in the study of pressure drop in helices. Regrouping the variables accordingly, Hc' takes the form 1+ φ(N, Re, D/Dh, r/D) in which all of the parameters are dimensionless.

In attempting to establish the functionality of Hc' with the various variables, the following tables and curves were prepared: Tables III and IV, and Figures 14, 15, 16 and 17. The tables list the variables for each helix at Reynolds Numbers 2x10^4 and 10^5. The figures show the observed variation of Hc'-1 with each of the four variables, N, Re, D/Dh and r/D.

Variation of Hc' with N and Re. Because of the paucity of data no conclusions reached regarding the relationship of Hc' and any of the variables can be considered concrete. However, from a study of Figures 14 and 15, it appears that Hc' is independent of N, the number of turns of the helix, and quite insensitive to Reynolds Number. The range of values of N is considered sufficient to substantiate somewhat the independence of Hc' and N. Contrarily, the range of Reynolds Numbers is small and makes caution necessary in concluding that the curvature correction is generally insensitive to variations in Reynolds Number. Also, in several instances the measurement of pressure drop at high Reynolds Numbers was made by two pressure gauges because the drop exceeded the range of the manometers available. The resulting loss of accuracy is reflected in many of the curves but is not present in Figure 15.

Variation of Hc' with D/Dh. Figure 16 shows the variation of Hc' with the ratio of tube to helix diameters, D/Dh, as determined by the experiments. Also shown for comparison is the correction factor Ac (= 1 + 3.5D/Dh). The data indicate an increase in Hc' with D/Dh with the exception of helix #10 (Hc' = about 0.07).

Variation of Hc' with r/D. Figure 17 indicates an increase in the correction, without exception, as the relative roughness increases. It is important to notice at this point the value of the correction for helix #10 and its position on Figures 14, 16 and 17. This helix was fabricated from one-half inch tubing with a value of D/Dh comparable to the other helices but with a low relative roughness value. The correction, Hc'-1, for this helix is very low (approximately 0.07) which makes it appear a wild point on Figures 14 and 16. However, in Figure 17 this value follows the trend of the other helices comparatively well. This fact may be the most important finding of the experiment for it indicates that helical pressure drop may be principally a function of relative roughness.

Summary of Results. Subject to the rather severe limitations and the assumptions of the experiment, the following conclusions may be drawn from the data:

1. the correction factor is apparently independent of the number of turns of the helix,

2. the effect of Reynolds Number on the correction is almost negligible over the range studied,

3. the correction appears to increase with the ratio of tube to helix diameters, with one marked exception,

4. the correction increases as the value of relative roughness increases, and

5. questionable evidence suggests that relative roughness, rather than the ratio of tube to helix diameters, may be the most significant variable involved in helical pressure drop.

CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS. Very limited study of ten helices formed from small, comparatively smooth circular tubing and operating at Reynolds Numbers between 10,000 and 100,000 indicates that the increased pressure drop due to curvature is a function of relative roughness, r/D, ratio of tube to helix diameter, D/Dh, and possibly Reynolds Number. There is questionable evidence that relative roughness may be the most significant of these parameters.

RECOMMENDATIONS. Certain applications of helical conduits, such as the cooling passages of regeneratively cooled rocket motors, require that pressure drop be held to a minimum. It would seem prudent in these cases to be especially painstaking in polishing the interior surface of such helices to minimize the possible compound effect of roughness on the pressure drop.

Recommendations for Further Investigation. The following suggestions are made for future investigation of this subject:

(a) increase the scope of the study to include:

1. a variety of tubing cross section shapes and sizes,
2. a greater range of Reynolds Numbers,
3. a greater variety of helical diameters, and
4. a greater variety of relative roughness values of the helices;

(b) if practicable, machine several helices and straight sections to duplicate exactly the degree and nature of surface roughness;

(c) investigate thoroughly the matter of measuring differential pressure at high pressure levels with the view of maintaining acceptable accuracy at high Reynolds Numbers; and

(d) investigate and experiment with the processes available for varying the interior surface of tubing, i.e., sand blasting, mechanical and hydraulic honing, and electrolytic polishing plus any others discovered, in order to be able to produce an interior surface of predictable roughness.

TABLE I

DETAILS OF HELICAL TEST SECTIONS

(1) HELIX NO.	(2) D_h INCHES	(3) D INCHES	(4) STR. LEADS* INCHES	(5) L INCHES	(6) NO. OF TURNS	(7) r MICRO-IN	(8) r/D $x10^4$
1	3.41	0.305	9.63	32.15	3	37.5	1.23
2	3.46	0.305	9.75	54.60	6	43.5	1.43
3	3.46	0.305	8.88	131.00	12	48.0	1.57
4	5.09	0.305	12.62	48.25	3	46.0	1.51
5	5.08	0.305	11.63	95.70	6	43.3	1.42
6	5.15	0.305	11.75	145.60	9	42.0	1.38
7	7.51	0.305	13.13	70.90	3	43.0	1.41
8	7.59	0.305	13.50	143.00	6	43.0	1.41
9	36.00	0.305	12.00	113.20	1	36.0	1.18
10	5.69	0.430	12.00	107.20	6	42.0	0.98

NOTE: All helices were tightly wound, i.e., pitch equal to outside diameter of tubing.

* By "straight leads" is meant the straight integral lengths of tubing extending tangentially from each end of the helix. The sum of these two lengths is listed in the table.

TABLE II

DETAILS OF STRAIGHT TUBE TEST SECTIONS

(1) IDENTIFYING NUMBER	(2) r MICRO-IN	(3) r/D $x10^4$	(4) PROCESS
1	37	0.861	SANDBLAST
2	37	0.861	"
3	34	0.792	"
B	42	0.978	"
C	45	1.050	"
X	25	0.582	ELECTROPOLISH
XI	26	0.605	"

NOTE: All straight test sections were prepared as five foot lengths of one-half inch stainless steel tubing of wall thickness 0.035 inches. Prior to testing, a one-foot length was cut from one end of each section to determine the pressure tap corrections as described under PROCEDURE.

TABLE III

ANALYSIS AT Re = 2×10^4 SHOWING APPARENT INCREASE OF FRICTION FACTOR (OBSERVED) OF HELIX OVER STRAIGHT PIPE

(1) HELIX NO.	(2) N	(3) r/D $\times 10^4$	(4) D/D_h	(5) f'	(6) f_o	(7) OBSERVED INCREASE PER CENT
*1	3	1.23	.089	.0262	.0370	41.2
*2	6	1.43	.088	.0263	.0440	67.4
3	12	1.57	.088	.0263	.0350	33.1
4	3	1.51	.060	.0263	.0330	25.5
5	6	1.42	.060	.0263	.0324	23.2
6	9	1.38	.059	.0263	.0345	31.2
7	3	1.41	.041	.0263	.0340	29.3
8	6	1.41	.040	.0263	.0330	25.5
9	1	1.18	.0085	.0262	.0324	23.7
10	6	0.98	.076	.0258	.0277	7.4

* Erratic results caused by local fouling in conduit. Not considered in analysis.

Note. Helix No. 10 was formed from [illegible]" tubing with a helical diameter of 5.69 inches.

TABLE IV

ANALYSIS AT $Re = 10^5$ SHOWING APPARENT INCREASE OF FRICTION FACTOR (OBSERVED) OF HELIX OVER STRAIGHT PIPE

(1) HELIX NO.	(2) N	(3) r/D x10^4	(4) D/D_h	(5) f'	(6) f_o	(7) OBSERVED INCREASE PER CENT
*1	3	1.23	.089	.0186	.0272	50.5
*2	6	1.43	.088	.0187	.0321	71.7
3	12	1.57	.088	.0188	.0257	36.7
4	3	1.51	.060	.0188	.0269	43.1
5	6	1.42	.060	.0187	.0247	32.1
6	9	1.38	.059	.0186	.0258	38.6
7	3	1.41	.041	.0187	.0258	37.9
8	6	1.41	.040	.0187	.0240	28.9
9	1	1.18	.0085	.0186	.0228	22.6
10	6	0.98	.076	.0184	.0197	7.07

* Erratic results caused by local fouling in conduit. Not considered in analysis.

Note: Helix No. 10 was formed from $\frac{1}{4}$" tubing with a helical diameter of 5.69 inches.

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MANUFACTURE OF THE HELICES

The helical test sections were manufactured as follows:

1. The inner surface of the tubing was coated with light machine oil and the entire tube heated in boiling water.

2. The tube was filled with a molten low-boiling-point metal known as "Cerrasafe" while immersed in the heating bath.

3. When cool, the tube was formed by hand around a circular pipe of suitable diameter.

4. The helix was then boiled in water to remove the metal filler and washed out with a steam jet for the final cleaning.

The maximum distortion of cross section created by this technique was a 1.3 per cent decrease in diameter in the direction of the helical radius. The conduit was therefore considered circular in cross section throughout the investigation.

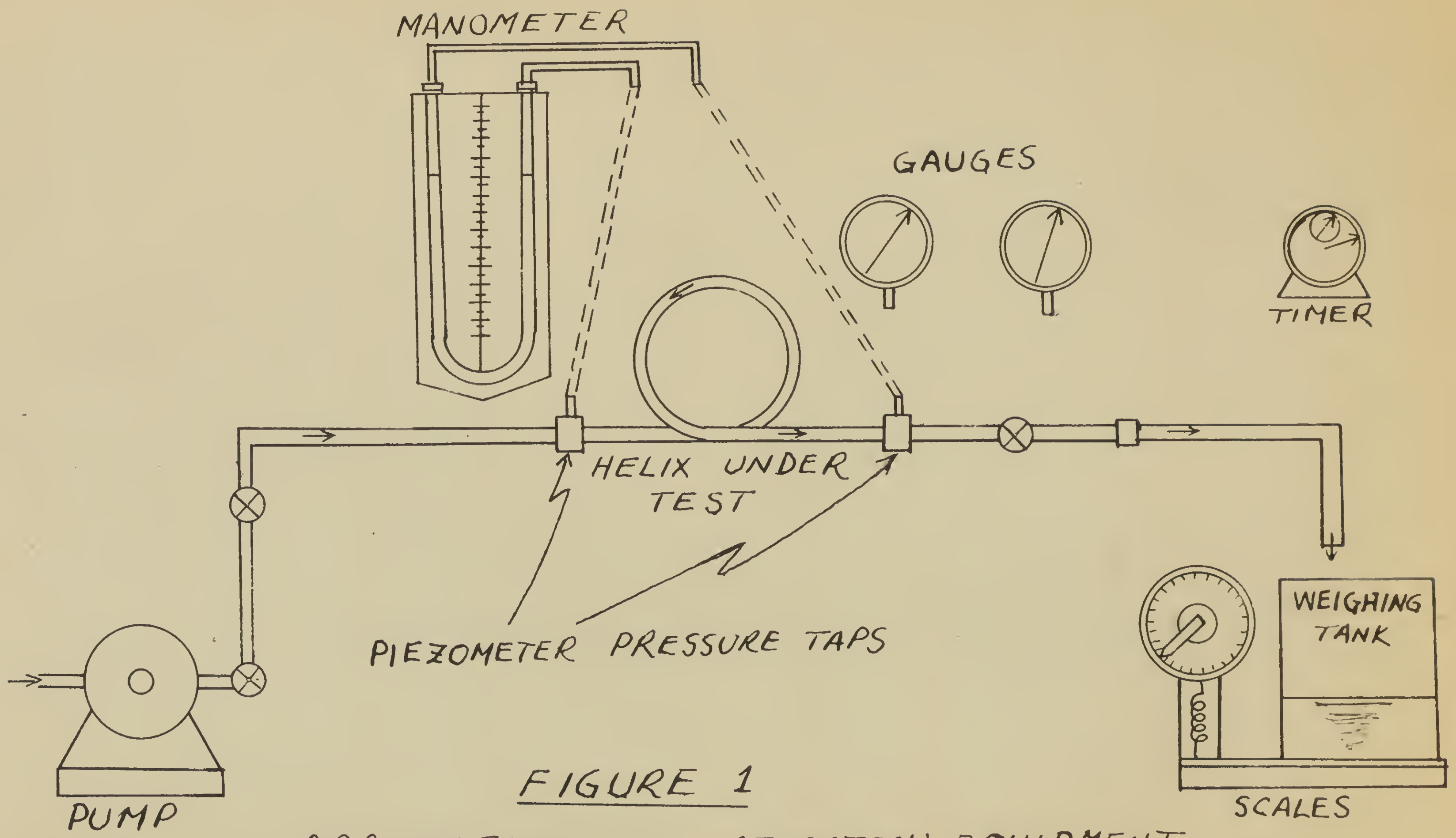


FIGURE 1

ARRANGEMENT OF LABORATORY EQUIPMENT

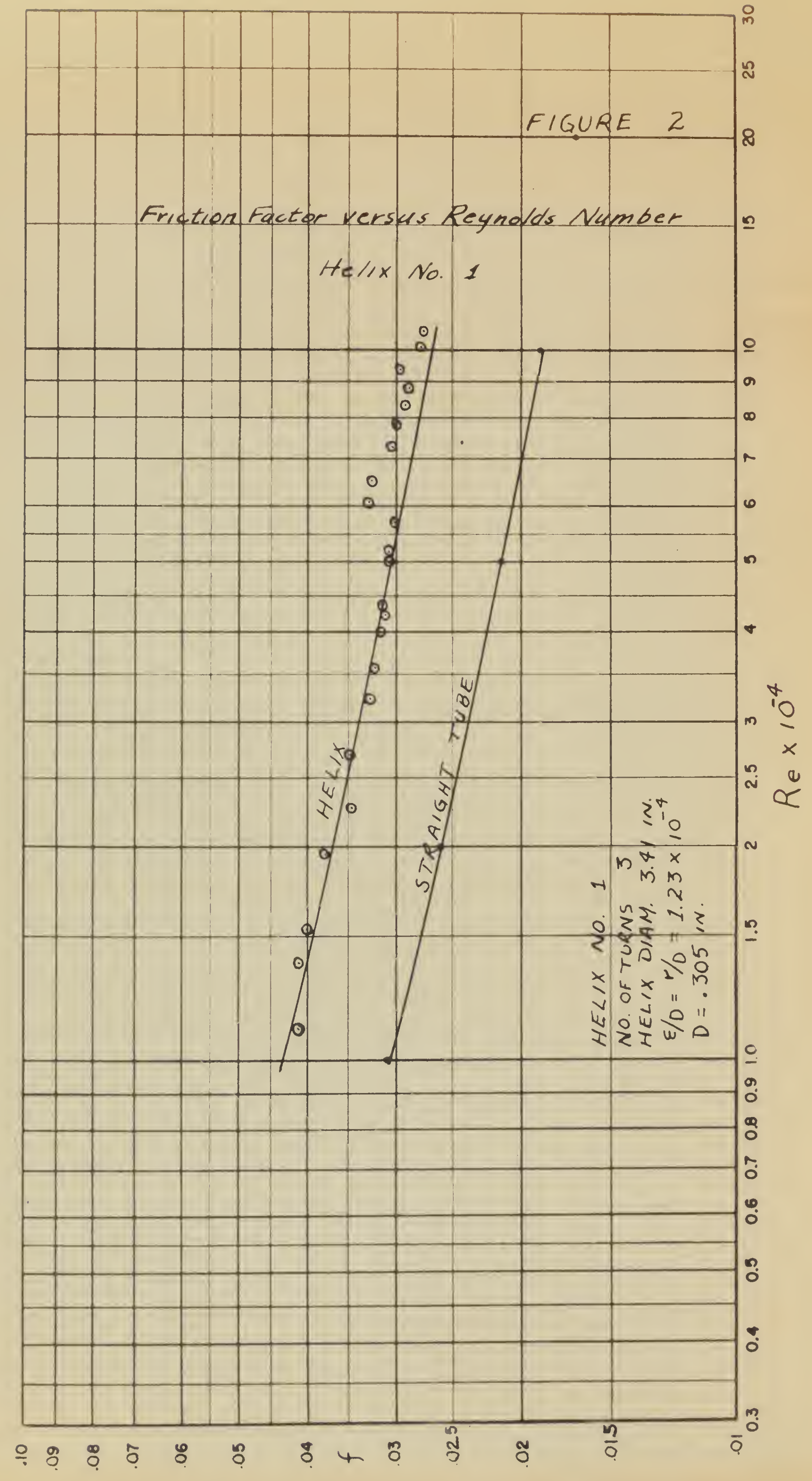


FIGURE 2

Friction Factor versus Reynolds Number

Helix No. 1

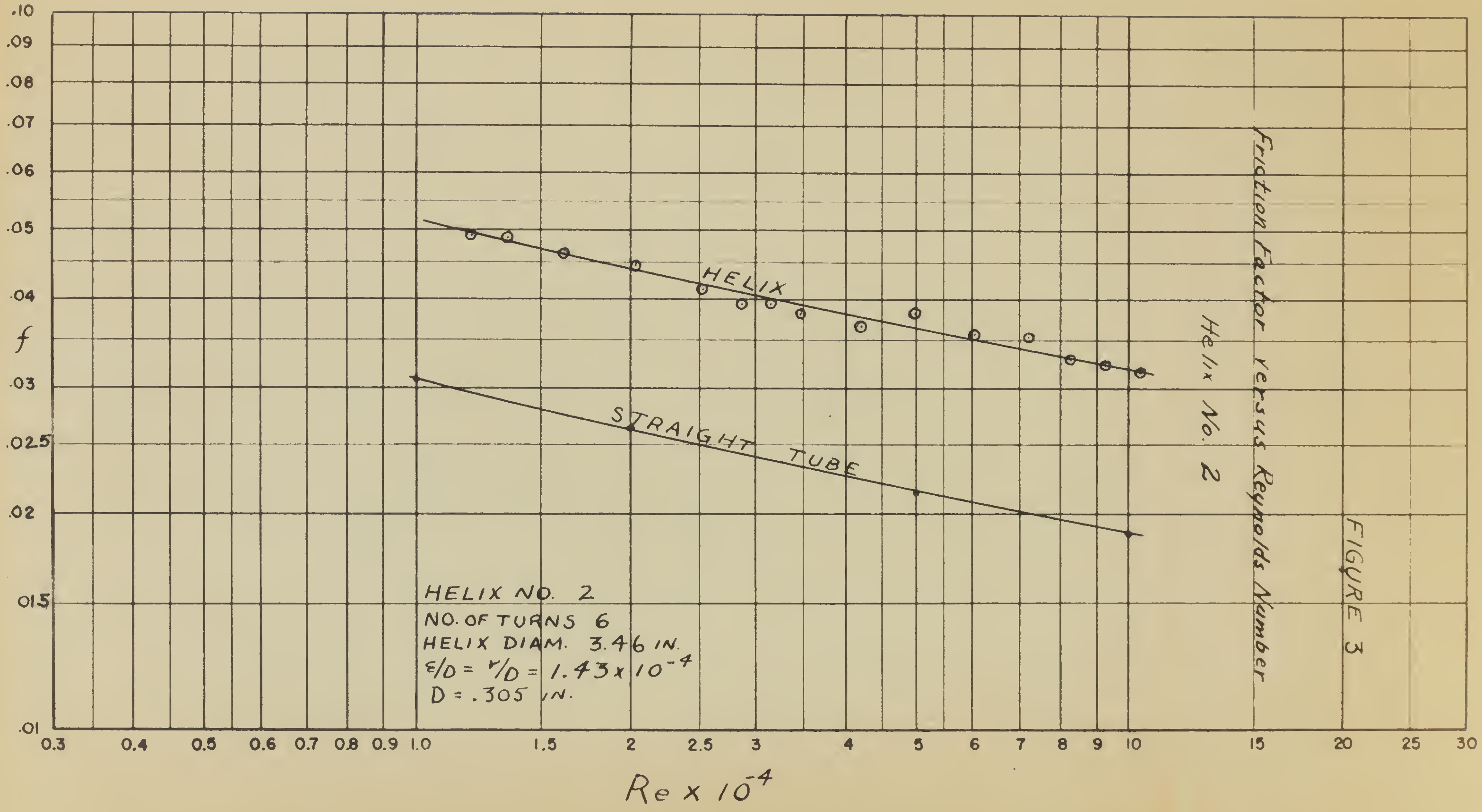


FIGURE 3

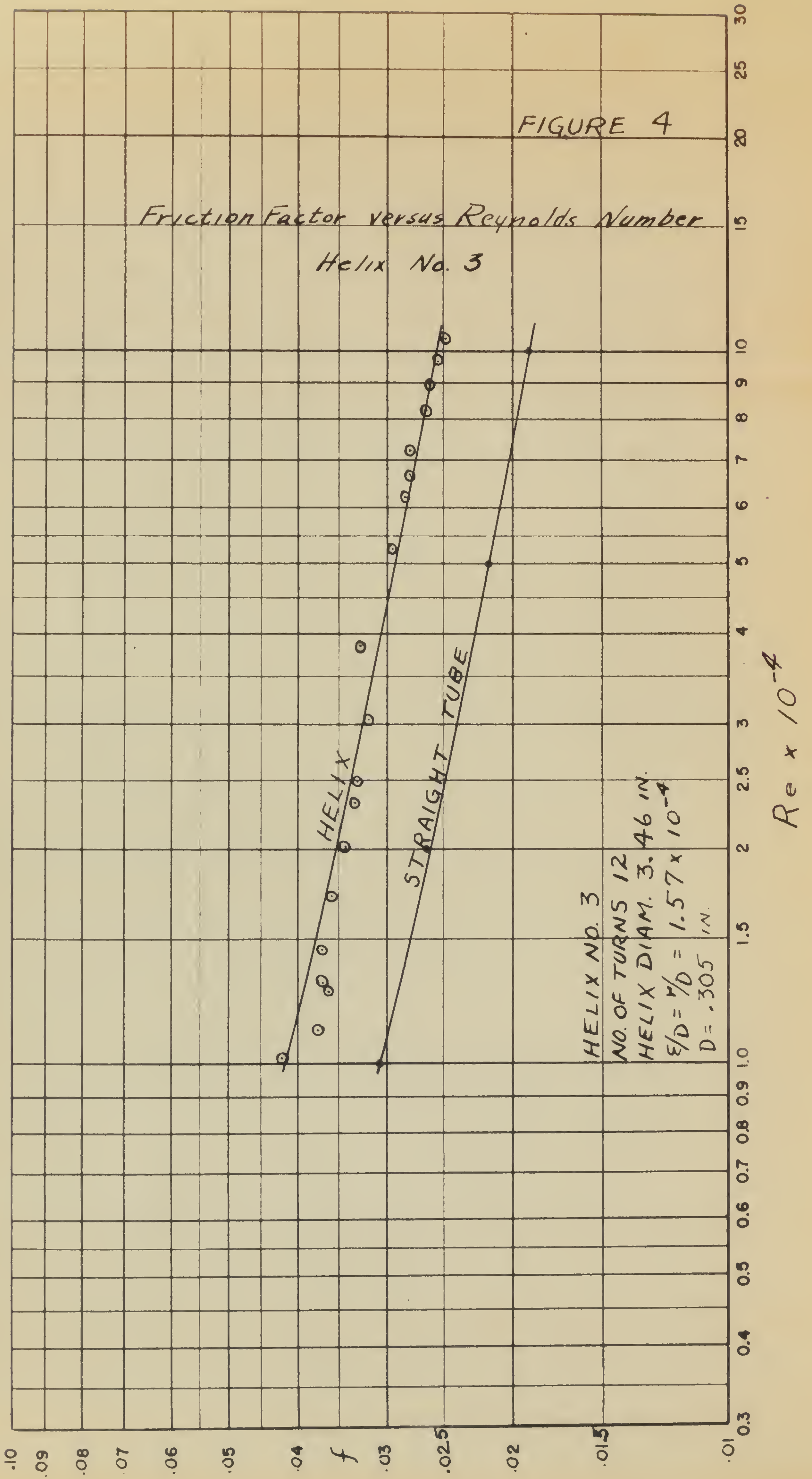
Friction Factor versus Reynolds Number

Helix No. 2

FIGURE 4

Friction Factor versus Reynolds Number

Helix No. 3



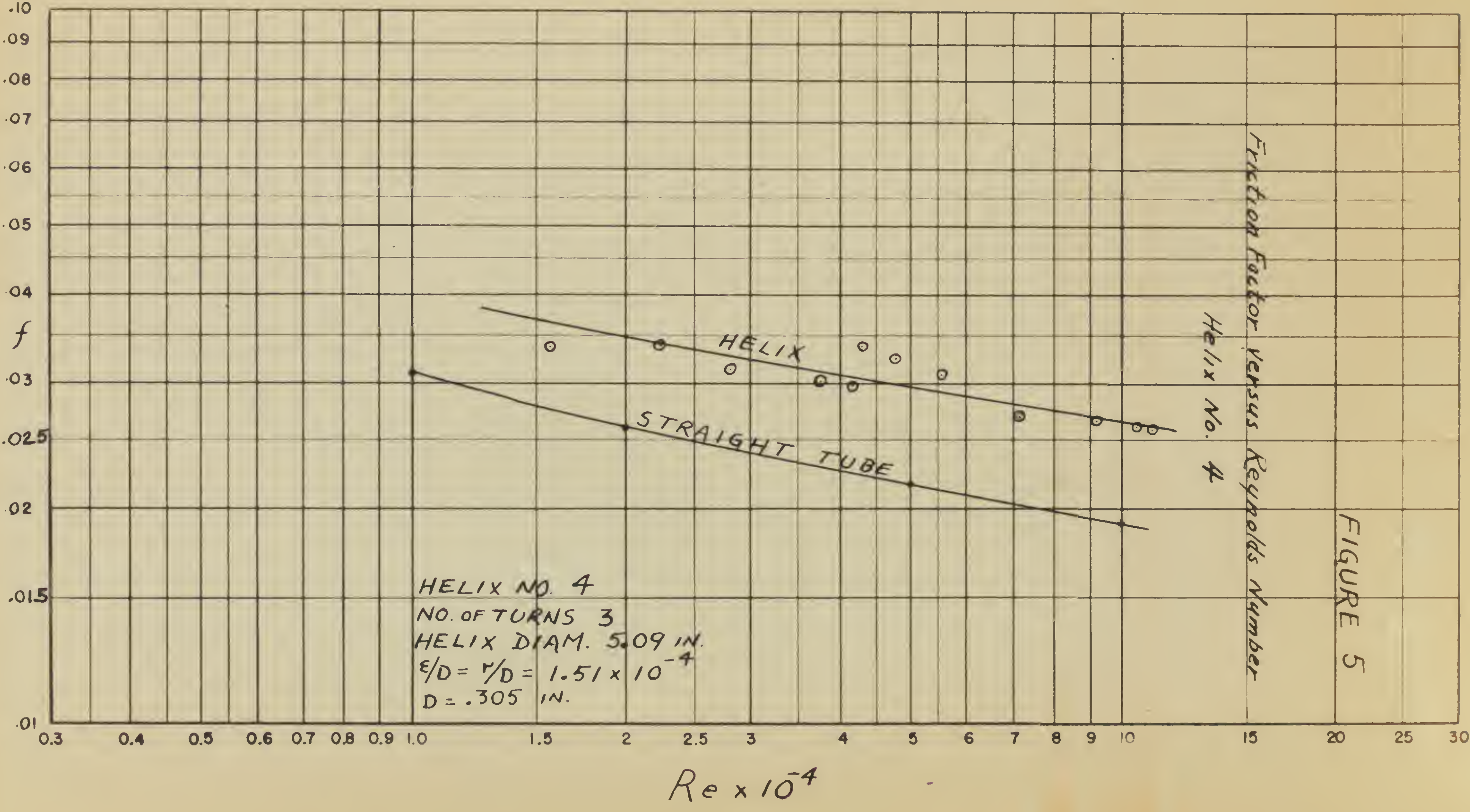


FIGURE 5

Friction Factor versus Reynolds Number

Helix No. 4

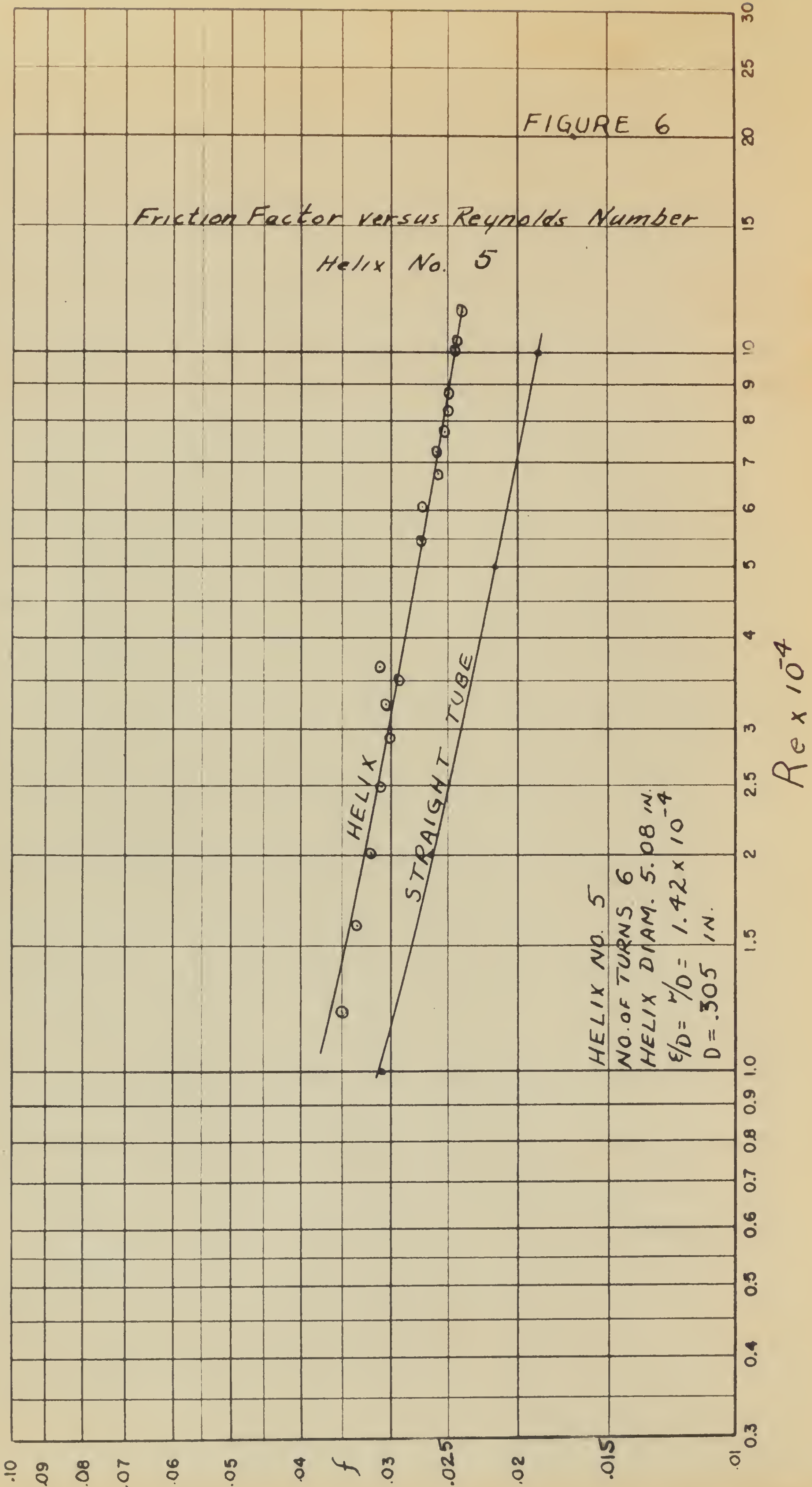


FIGURE 6

Friction Factor versus Reynolds Number

Helix No. 5

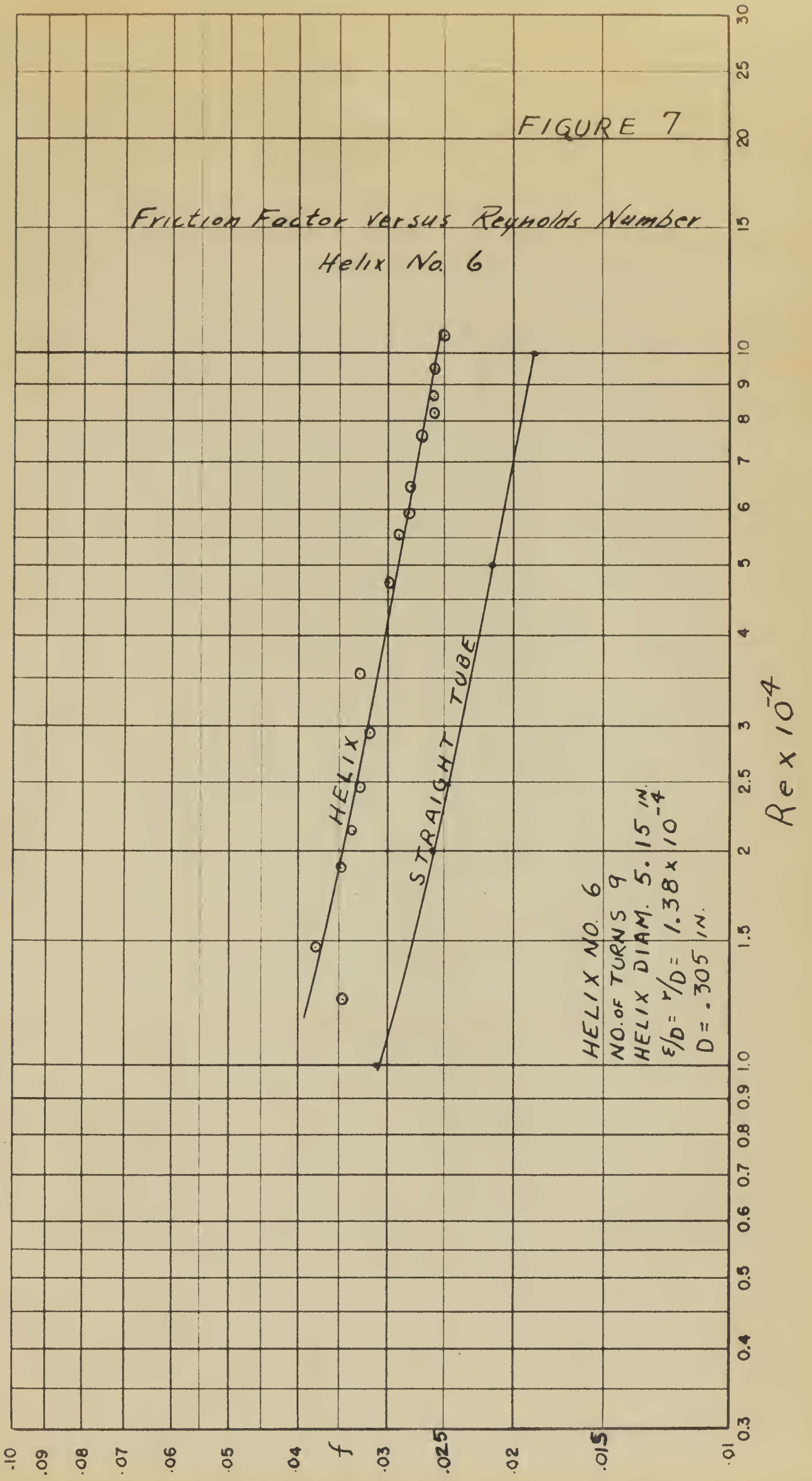


FIGURE 7

Friction Factor versus Reynolds Number

Helix No. 6

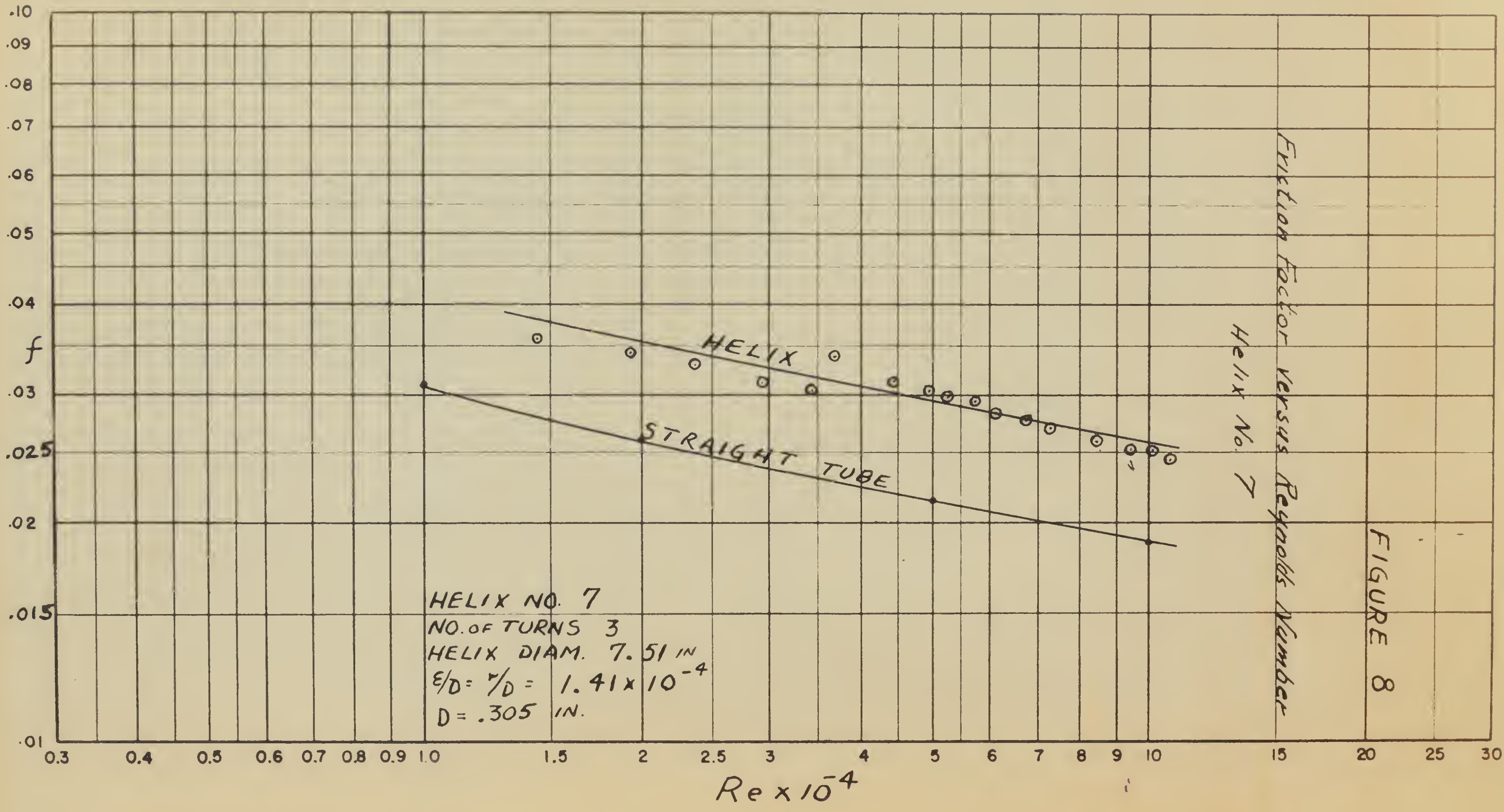


FIGURE 8

Friction Factor versus Reynolds Number

Helix No. 7

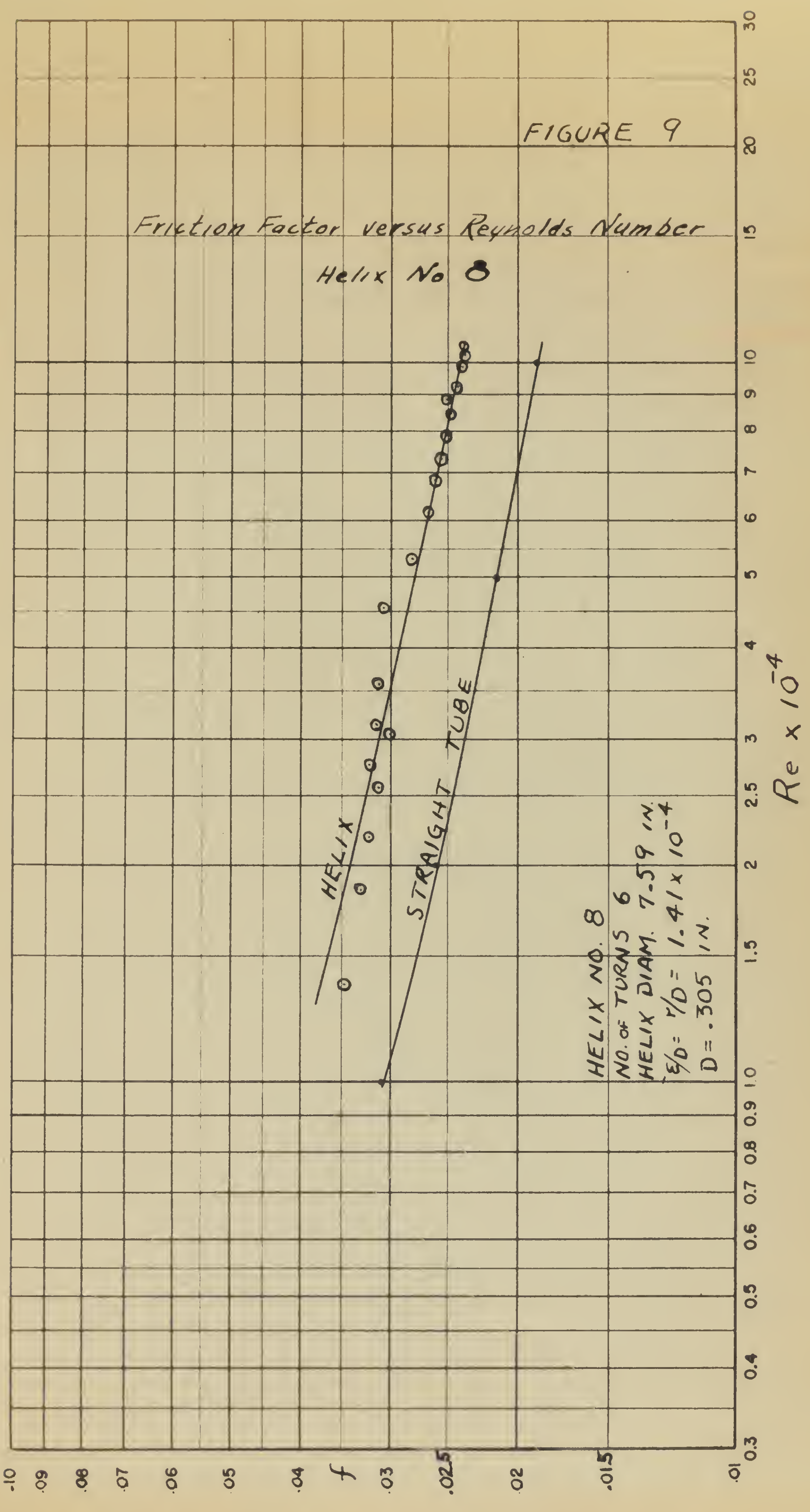


FIGURE 9

Friction Factor versus Reynolds Number

Helix No 8

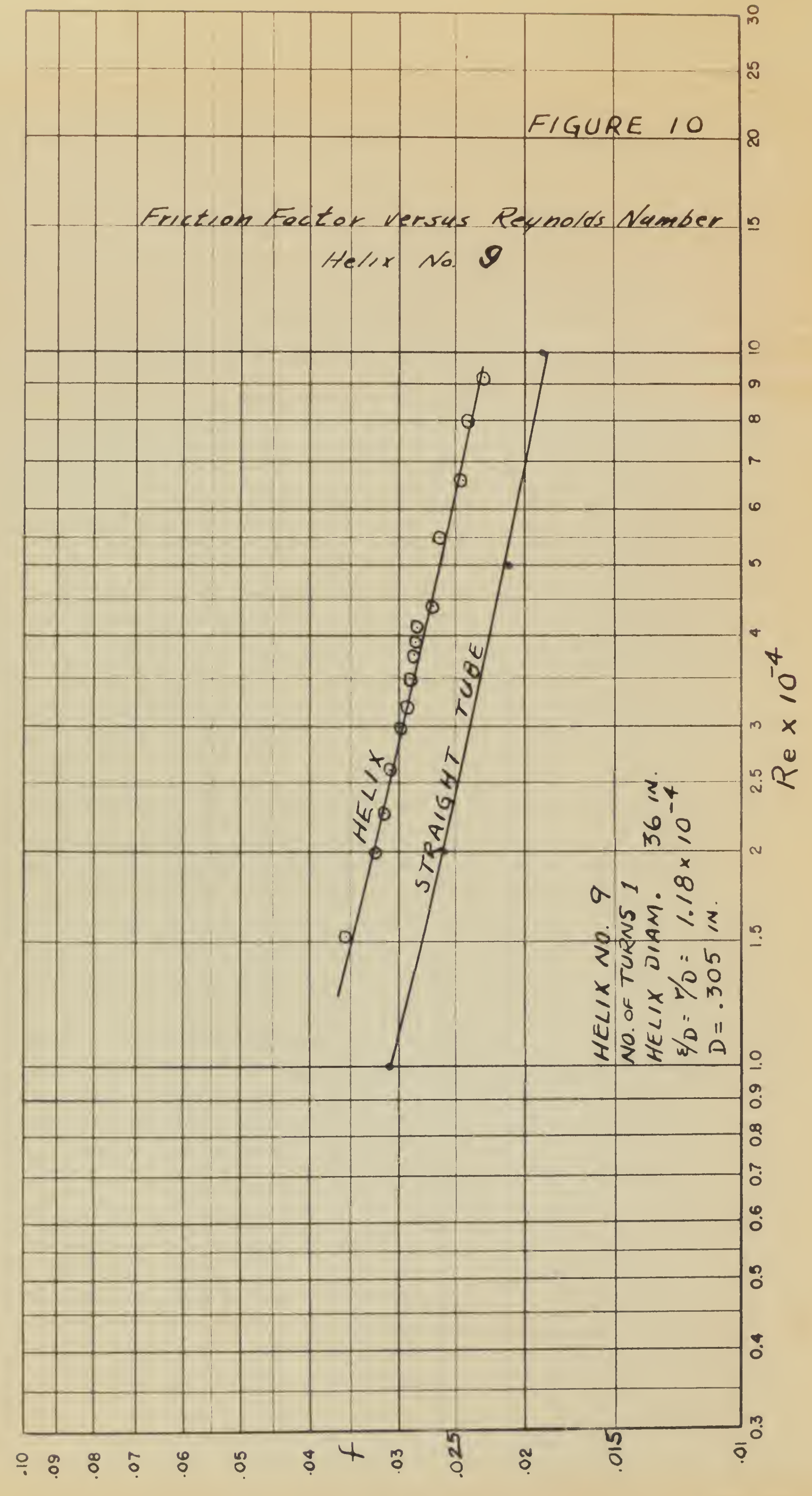


FIGURE 10

Friction Factor versus Reynolds Number
Helix No. 9

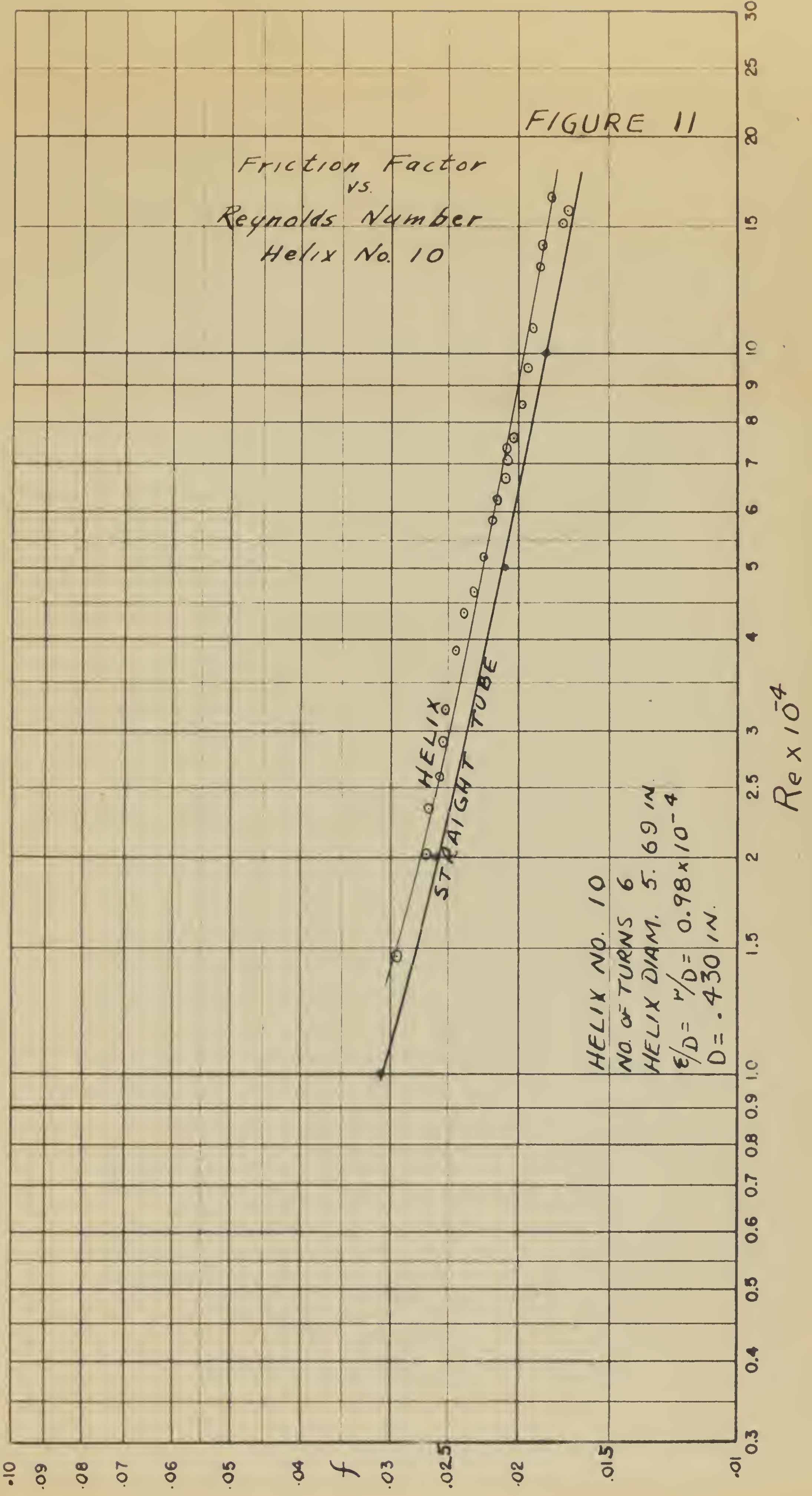


FIGURE 11

Friction Factor
vs.
Reynolds Number
Helix No. 10
HELIX
STRAIGHT TUBE
HELIX NO. 10
NO. OF TURNS 6
HELIX DIAM. 5.69 IN.
ε/D = r/D = 0.98×10⁻⁴
D = .430 IN.
f
.10
.09
.08
.07
.06
.05
.04
.03
.025
.02
.015
.01
Re x 10⁻⁴
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
1.5
2
2.5
3
4
5
6
7
8
9
10
15
20
25
30

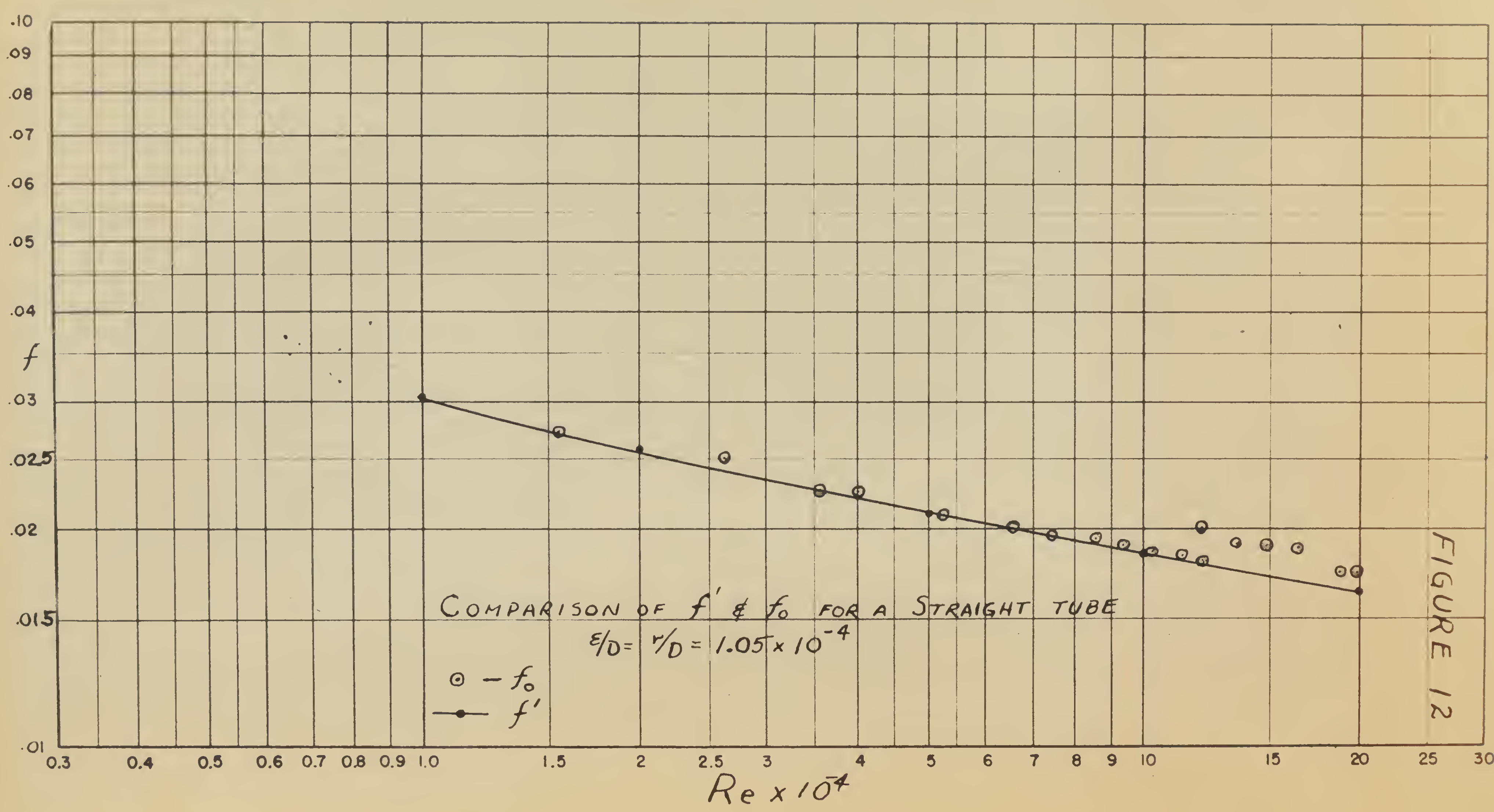


FIGURE 12

COMPARISON OF f' & f_o FOR A STRAIGHT TUBE

$\varepsilon/D = r/D = 1.05 \times 10^{-4}$

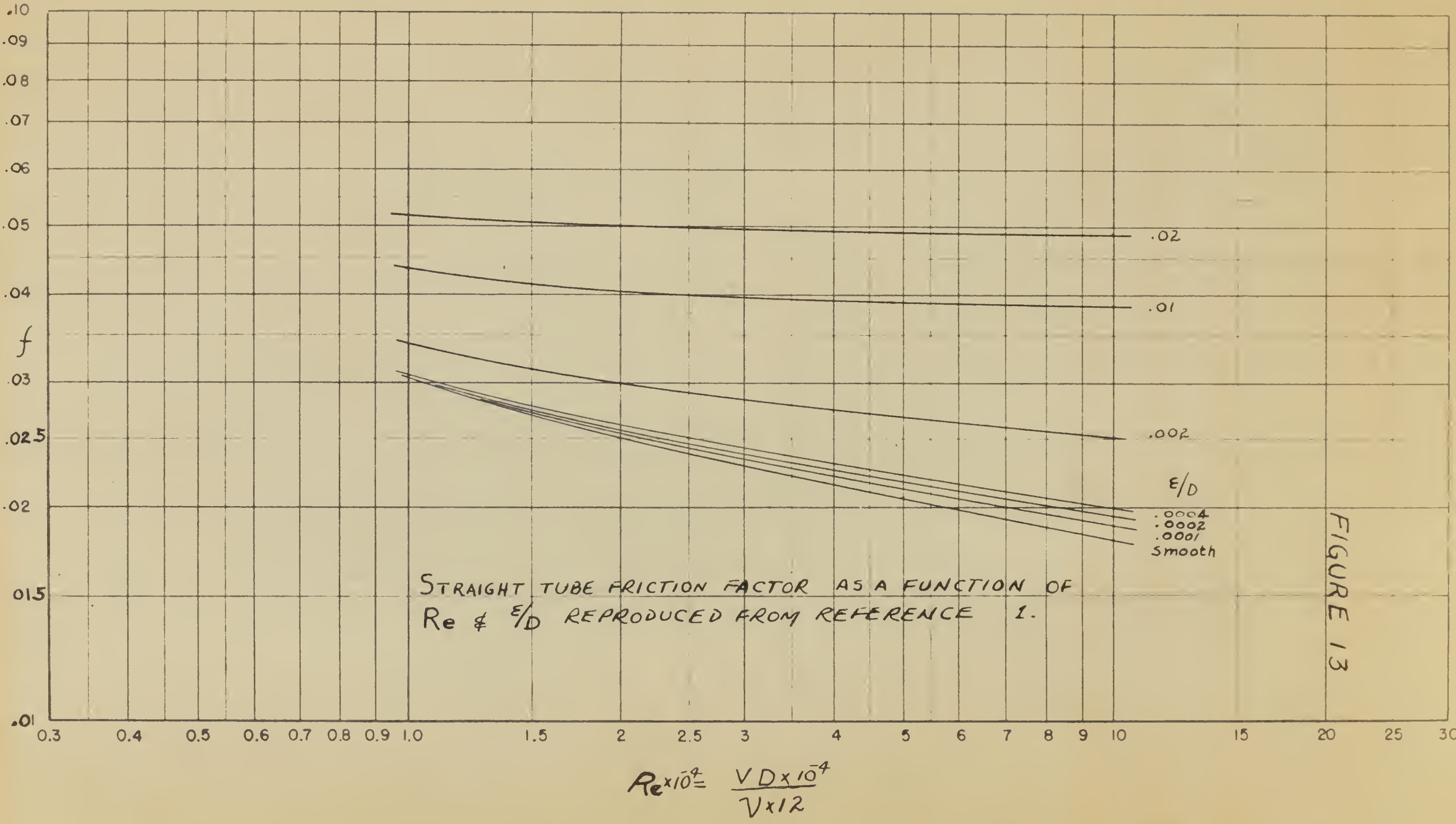


FIGURE 13

STRAIGHT TUBE FRICTION FACTOR AS A FUNCTION OF Re & ε/D REPRODUCED FROM REFERENCE 1.

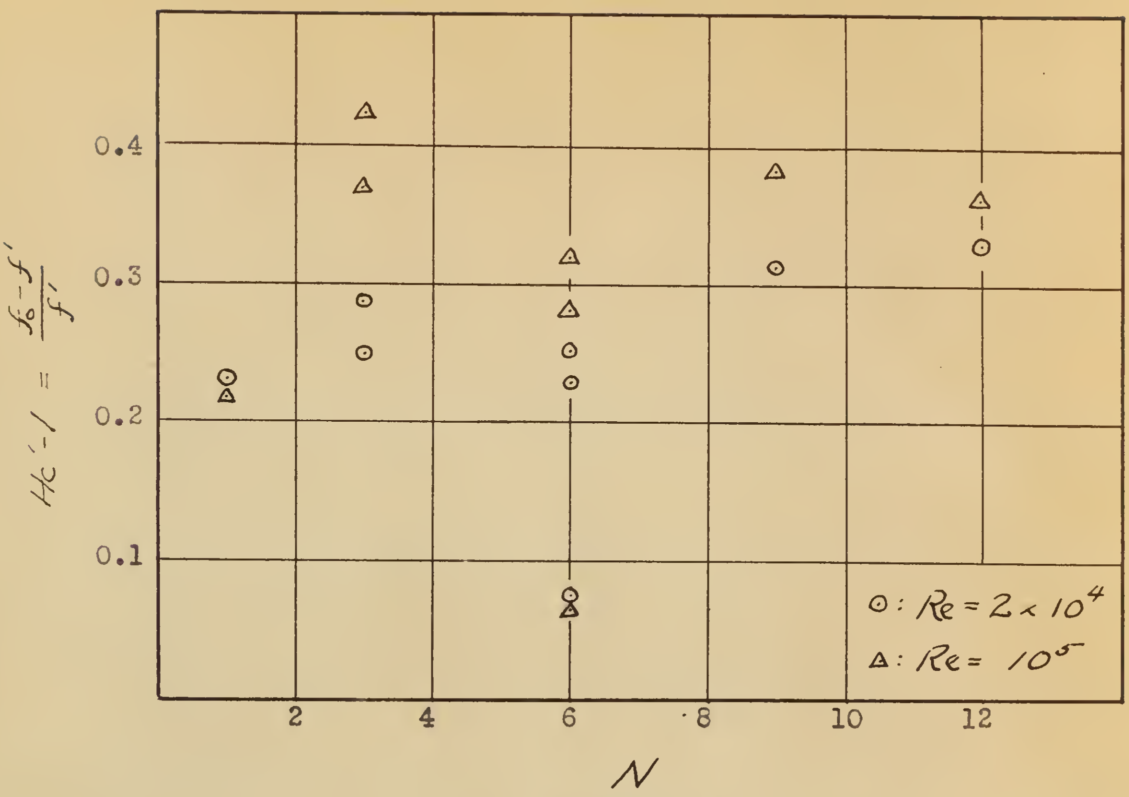


FIGURE 14
Hc'-1 vs. Number of Turns

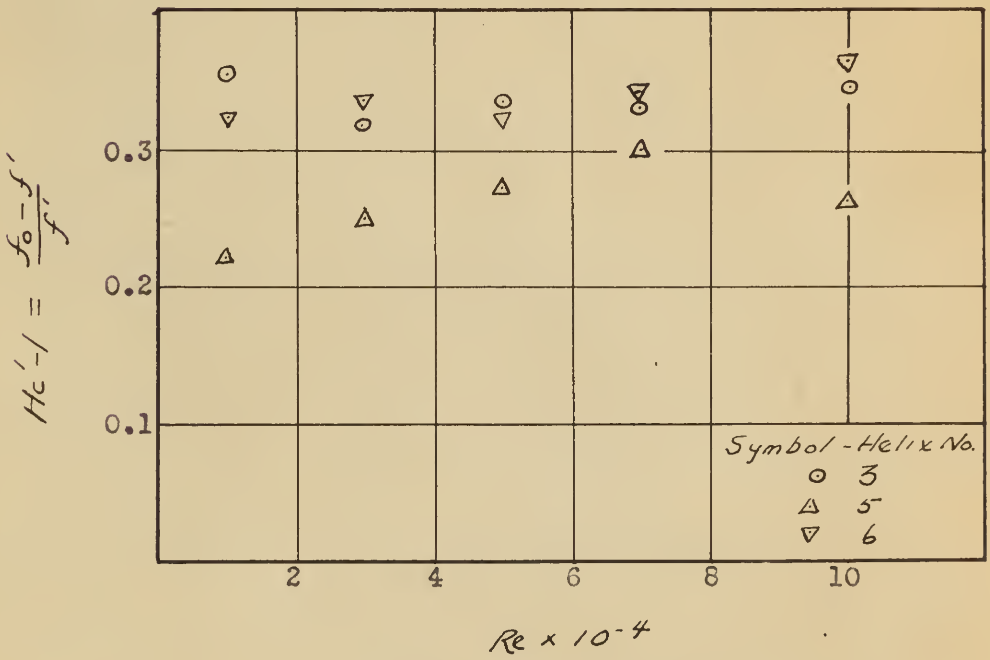


FIGURE 15
Hc'-1 vs. Reynolds Number

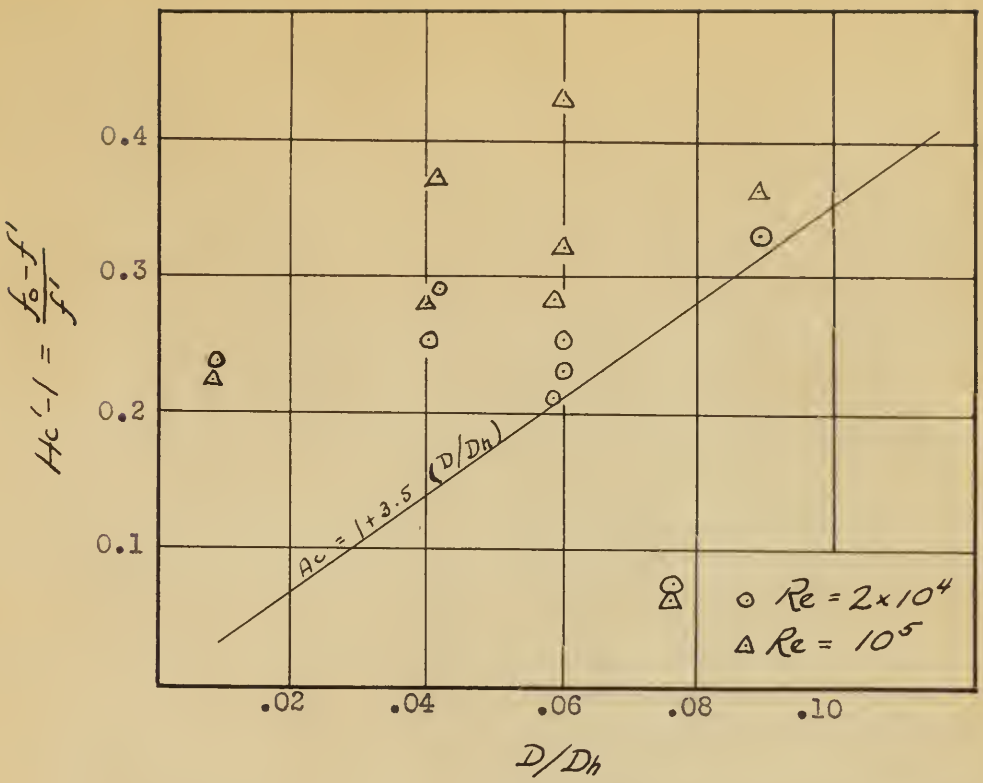


FIGURE 16
Hc'-1 vs. Diameter Ratio

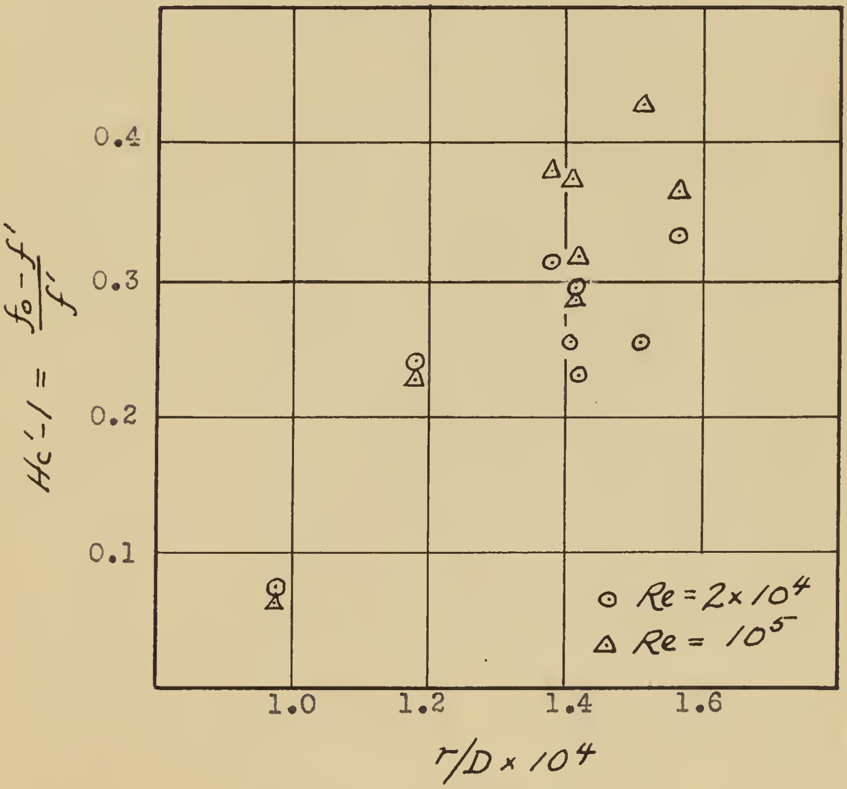


FIGURE 17
Hc'-1 vs. Relative Roughness

Fig. 46

$NF_8(70)^{40}$

No. 35

$\alpha = 38^\circ$

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